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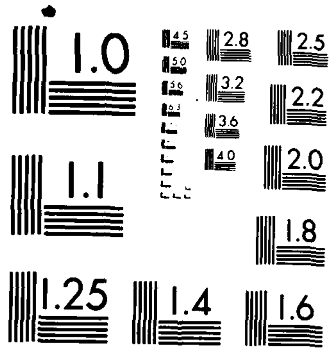

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MACHINABILITY DATA BASES FOR METAL CUTTING

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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Machinability date bases are discussed with respect to content, form and methods. Machinability data is needed to implement the factory of the future. Therefore, data sources and current formulas are featured in addition to formation of structures.

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INTRODUCTION

Machinability data bases are collections of information which are designed to assist engineers, designers and planners to choose efficient tools that match the machining operation and the work material. Considerable machinability research has been performed and the results are cataloged. The Machining Data Handbook published by the Machinability Data Center sponsored by the US Army Materials and Mechanics Research Center and the Tool and Manufacturing Engineers Handbook published by the Society of Manufacturing Engineers Handbook are notable in this regard. (1, 2) The casual observer of machinability information is immediately struck by the immense amount of data, the interaction of different data, and the complexity of the tool-material relationship. To make machinability data more useful, several attempts are underway to create computer supported machinability data bases. As discussed below, machinability data bases are required for the development of the factory of the future. This report discusses machinability data usage, relationships, and structures.

MACHINABILITY DATA BASE

A data base is a collection of interrelated information and their relationships. The purpose of the data base is to store information efficiently while allowing multiple users to quickly retrieve information on demand. (3) A machinability data base is a collection of data that describes the machining process under differing work and tool configurations. A large part of the data is stated explicitly as numbers, while other data is accurately represented mathematically. The users of a machinability data base are product

engineers and designers, process and production engineers and planners, machine tool programmers, tool designers, and researchers.

MACHINABILITY DATA BASE USAGE

The primary purpose of a machinability data base is support process planning for machining operations. Process planning is the art and science of converting an engineering design into precise instructions to manufacture a product. The engineering design is a combination of drawings, written specifications, and standard references. The design information is analyzed to determine the machining operations performed, the materials involved, and the tolerances allowed. This establishes a path through a given plant and the specification of machines and materials necessary to perform machining operations. At this point, the machinability data base is used with knowledge of the machine, specified operation and tolerances to specify tooling, cutting fluid and detailed operational requirements; including machine horsepower, spindle speed, work feed, depth of cut, time of cut and economic factors. The results of process planning is a route sheet which precisely defines the raw materials, the processes, the machines, the tooling, incidental equipment, and the operational parameters of the processes to manufacture a part. (4, 5, 6)

Computer-aided process planning is used in several manufacturing facilities today. Variant systems, which rely upon modification of a previous process plan by a human process planner, are greatly enhanced if the process planner can immediately access a machinability data base. This facilitates computational efficiency and results in uniform process plans.

Machinability data is an essential part of generative computer-aided process planning systems. A generative system in a computer integrated manufacturing system, receives a design from a computer-aided design and engineering data base, and creates a route sheet by the use of analytic logic. Without machinability data, there is no basis for generating specific machine instructions required on the routing. (7)

Mechanical, industrial, and manufacturing engineers and designers require descriptive data and mathematical relationships concerning product design, process variables, material characteristics, economic analysis, and producibility. A secondary purpose for a machinability data base is to support the efforts of engineers and designers in the development of manufacturing products and processes.

A product can be made by differing processes and a process can be executed under several vastly different conditions. These differences may be crucial to the reliability or performance of the design. Thus, the designer may need to specify process parameters to meet his design goal. Consideration of process cost should also be a primary consideration to a design engineer. A successful design is not only reliable and producible, it is also economically efficient. A machinability data base supports computation of economic factors in evaluation of machining operations. (8)

MACHINABILITY DATA DEFINITION

Machinability is a relative term that parametrically relates work material properties, tool materials, tool life, cutting speeds, surface finishes, power

consumption, and other factors of the machining process. The definition of machinability is imprecise. Most authors describe good machinability without expressing a universal definition. This has the pronounced effect of the formulation of a data base to meet the needs of machining process design.

There is disagreement concerning what machinability should measure, and how it should be stated. Some favor certain variables such as tool life, and ignore others such as surface finish. Frederick W. Taylor, who many consider the father of modern industrial engineering, identified twelve variables that affect a choice of cutting speed. (9) Yet, he is most remembered only for the use of two: tool life and material. (10) While machinability is understood to be a measure of the difficulty or ease of cutting a given material, the data is based on empirical results only loosely supported by a theoretical foundation. (11) Often, research conclusions appear to be contradictory. The situation is worsened by the economic importance of several factors which overshadows otherwise significant observation of the machining process. For these reasons, a single machinability factor for each material-tool combination is not acceptable for universal use. (12) Data management under these conditions is difficult, subject to potential structural revision and frequent information correction.

Variables which affect machinability include tool life, tool geometry, tool material, type of operation, workpiece material and conditions, cutting speed, work feed, cutting fluids, chip formations, tool and workpiece temperature, cutting forces, chemical interactions and costs. The quantification of these variables are the data elements in a machinability data base. Because of the

continuing study of machinability, growth in the number of variables and hence, the number of data elements, must be expected for machinability data.

The machinability data elements have been presented in both common and innovative forms. Cataloged information by tool vendors, industrial associations and research firms are available as reference works. At least one company developed an analog computer to compute machinability variables. (13) Another unusual manner of presenting the data was in the form of a slide rule. (14) A problem with these systems is that the data must be updated as new processes, tools and materials become available. Generalized equations which mathematically describe the machining process, such as the Taylor tool life equation, despite good results in a few areas, have been found inadequate for unlimited use by industrial part producers in the current state of the science. (15)

MACHINABILITY DATA SOURCES

The most voluminous source of data is the two volumes of the Machining Data Handbook published by the Machinability Data Center. This reference catalogs data for the twenty most common traditional machining operations in 61 work material categories. In addition, data from more than 18 non-traditional machining operations has been included. Other handbooks such as Tool and Manufacturing Engineers Handbook, published by the Society of Manufacturing Engineers and the Metal Handbook, Volume 3: Machining, are also excellent sources of data. This data has been collected from independent research, industrial research, tool specifications and theoretical computational methods. (16, 17, 18)

Another excellent source of data is tool manufacturers' literature. This data, while normally limited to the tools that the manufacturer sells, provides excellent insights into the properties of specified tooling. The machine tool builder specifications indicate machining capabilities and give specific instructions to process work materials. Several machinability ratings have been designed by the tool building industry to indicate machinability as compared to a standard material, normally B1112 steel at 200 BHN. One should be particularly careful in using these ratings as they are computed differently with widely diverse variable weightings. (19, 20)

If the opportunity exists, information may be generated internally by a data user. Certainly, an experienced user of machinability data will recognize blatant data errors which should be corrected. The data in a machinability data base can be at best only a guide to planning. This data will have to be massaged to reflect actual on site conditions. (21)

Information that is available in plant and measurable, includes horsepower, cutting forces, cutting vibrations, tool wear, work piece material, tool material, surface finish, and costs. Most of the data can be taken remotely with sensors and a data collection system. The remainder of the information is available from inspection records, piece part travelers which record the operation completion data and tool records. (22) When information has been taken, it must be integrated with existing data and modeling systems. This type of data collection and analysis system improves the information necessary for factory automation in addition to building an accurate operational data base.

MACHINABILITY DATA STRUCTURE

The growth of the use of computers for designing, engineering, planning and in automating the factory has led to a demand for machinability data in a computerized form. This also appears to be a solution to many of the problem areas above. Data base structures which are flexible and efficient have been designed to meet the needs of the machining industry. These designs permit updating as new methods, materials and information become available.

Analysis of data structures to support a given task starts with consideration of what information is already available, what functions the data base processor will perform and what information is expected as output. The conceptual input/process/output model (sometimes called the black box model) for a machinability data base has the following form: (23). (Fig. 1)

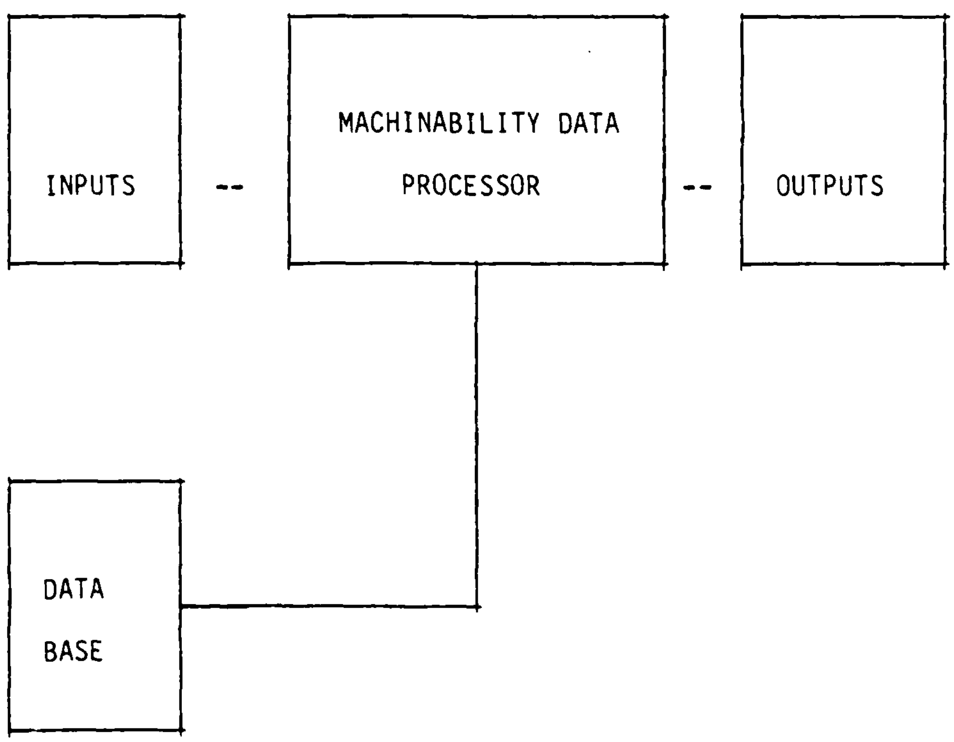

Figure 1. Conceptual Input/ Process/ Output model.

The input consists of primary keys and secondary keys. These are used to reference the data base as one uses the alphabet to find words in a dictionary. The primary keys identify significant categories within the data. Turning, face milling and grinding are examples of primary keys which identify operation types. Secondary keys are used to refine the search to a given data record or element. For example, a 0.015 inch depth of cut refines the data search to a specific record of information within the category of face milling.

An important factor in data base usage is simplicity of the input. The operator for a machinability data base will not, in general, be a computer specialist. According to James Martin, acceptable time to become proficient on a system designed for an untrained operator is one hour. (24) While it is expected that a user will be knowledgeable in use of machinability data, the method for retrieval should not be so complex as to require extensive training.

The machinability data processor has the functions of locating the data, editing the data and formatting the data for output. In systems where data is computed as a result of the input and/or the data base retrieval, the processor has the additional mission of mathematical manipulations. An effective processor is quick, responsive to the needs of the user and protected against failure from bad input or bad data in the data base.

The output ideally reflects the desires of the user by presenting usable information. The format should be easy to read and not cluttered with unnecessary information. If the output is designed for use by other computer systems, such as a computer aided process planning system, the data should be

organized into standard fixed length records to avoid waste of programmer's and maintenance personnel's time in attempting to analyze data transfers. If the capability exists, graphical output is desirable to tabular information.

HIERARCHIAL MACHINABILITY DATA BASES

Hierarchial machinability data bases are normally oriented with primary keys based upon operation type. Once the specified operation has been located, work piece material, condition and operational dimensions are used to determine tool properties. The tool properties are organized by tool materials. The tool material record will contain as data elements, speed, feed, tool geometry, cost per unit of operation and cutting fluids. The work material removal rate, the horsepower and economic costs are computed mathematically. The processor uses the input to extract further information from the data base and make any computations that may be required. This data, massaged into a suitable format, is the output presented on a computer terminal screen or printed. Data for use with a computer aided process planning system should be placed in a computer readable file.

Machinability data stored and retrieved in this manner is termed hierarchial or tree structured. This tree structure should not be confused with the multiple trees used with relational data bases which are described further on. In the case of hierarchial data, there is but one tree which accesses the desired data. Each node (i.e., where the tree branches,) must be traversed in a prescribed order from the top of the tree to desired data. Thus, the input must specify a path to retrieve appropriate machinability data. The data is organized descriptively in the following manner: (Fig.2)

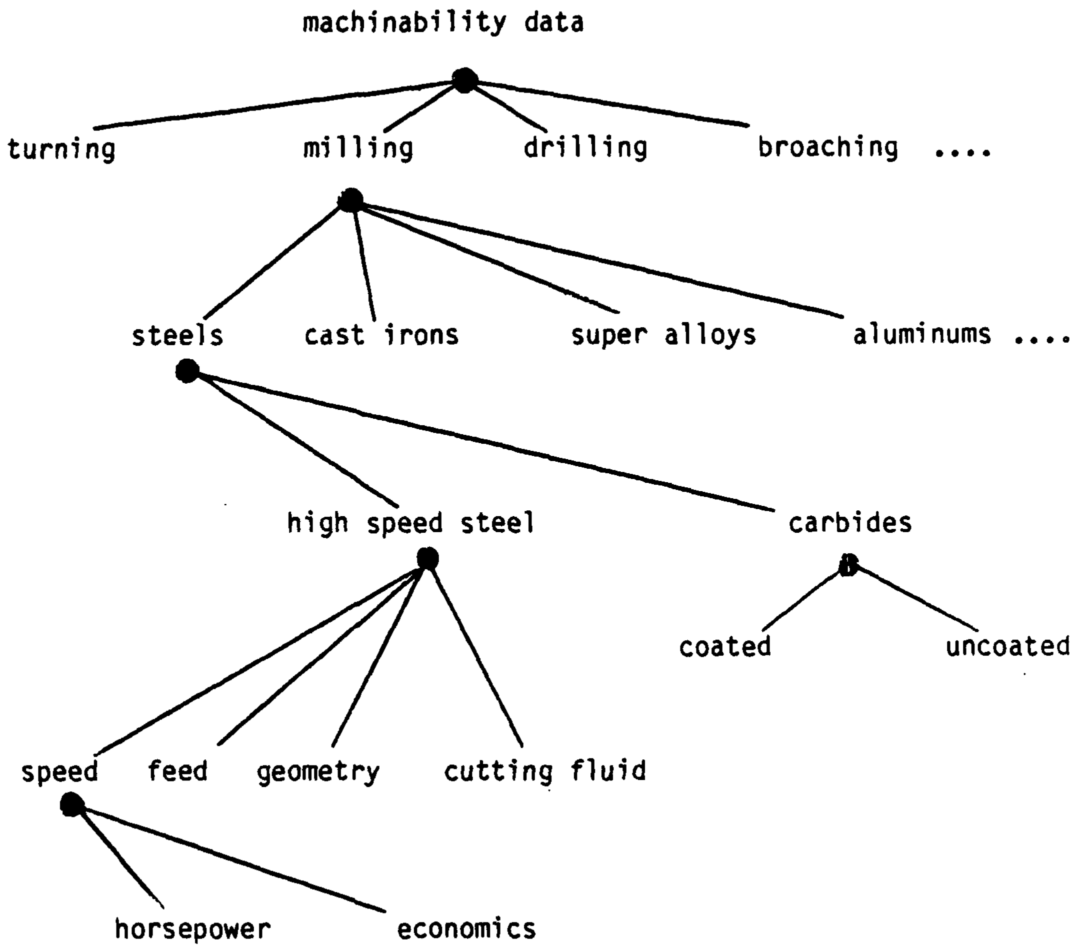

Figure 2. Hierarchial Machinability Data Base.

The information that is desired is near the bottom of the structure. However, this information cannot be accessed until the data above it has been extracted.

This structure can store and retrieve considerable amount of information efficiently. However, hierarchial data structures has a disadvantage in that an operator must be relatively well trained. The use of menus for selections can be used effectively to reduce the training requirement. Another disadvantage is the inability of accessing data which may be related to an element but not

properly a part of the access path to the element. For example, a query of the data base for all tool configurations which allow a 40 HP mill to perform a pocketing operation to a depth of three inches in AISI 4340 steel, BHN 300, could not be directly executed using the hierarchial structure given above. This flaw has been recognized as a problem with some machinability data bases. (25) Additionally, updating and modifying information has also been recorded as a problem. (26)

In a typical hierarchial machinability data base, the primary key inputs might be workpiece material, the workpiece condition, the type of machining operation and critical dimensions of the work. Using AISI 4340 high strength wrought steel, quenched and tempered, BHN 300, which is to be face milled with a depth of cut of 0.150 in. and width of cut is 3 in. as an example, the next step might be the selection of the tool material. The data base processor would identify three possible materials: high speed steel, carbide and coated carbide. A default tool material could be selected or the operator could specify the desired material. Assuming that high speed steel is the default tool material, the data base processor would then select a heavy cut abrasion resistant high speed tool steel such as M42. With a tool life of one hour, the recommended speed and feed are 85 fpm and 0.009 in. per tooth of the mill. The tool cutter geometry is specified next: axial rake angle 7.5 degrees, radial rake angle of 5 degreees, corner angle of 45 degrees, end cutting angle of 5 degrees, axial relief angle of 6 degrees and radial relief angle of 5 degrees. The type of operation, the tool material and the workpiece material and condition indicate that a medium or heavy duty emulsifiable oil or snythetic

should be used. Lastly, a computation of the metal removal rate and the horsepower required at the motor is made. For this example, a metal removal rate of 3.5 cubic inches per minute is expected. A dull tool (worst case) will require 6.5 horsepower at the motor. (27) Additional information concerning operation costs and tradeoffs for differing tool lives have not been computed for this example.

In the form of the model, the following occurred with the above hypothetical machinability data base processor:

INPUTS

material:
AISI 4340
QT BHN 300

operation:
face mill
doc = 0.150"
woc = 3.000"

DATA BASE

operation data
material data

tool geometry data

cutting fluid data

power requirements

PROCESS	OUTPUT
tool material selection	M42
tool life	60 minutes
feed selection	85 fpm
speed selection	.009" per tooth
tool geometry:	
axial rake	7.5 degrees
radial rake	5.0 degrees
corner	45.0 degrees
end cut	5.0 degrees
axial relief	6.0 degrees
radial relief	5.0 degrees
diameter	3.0 inches
teeth/tool	8 teeth/tool
cutting fluid	medium or heavy duty emulsified oil
power	3.5 cu in/min
	6.5 HP (dull

An example of a hierarchial data base is CUTDATA sold by Metcut Research Associates, Inc. Such systems by their nature tend to perform in the same manner as one would use a machinability handbook.

MACHINABILITY COMPUTATIONAL METHODS

Another approach to providing machinability data is to compute the date from formulas "on the fly" as it is needed. Good examples of such systems are the Carboloy(TM) Systems Computerized Machinability Program, FAST and EXAPT. Using dimensional analysis, multiple regression techniques and curve fitting methods, several formulas for machinability data have been derived which provide consistent results over a range of machinability variables. (28) These type of systems might not be categorized as a true data base by a purist as they do not perform the function of data storage and retrieval. But these systems do provide data on demand and are extensively used.

The grandfather of all machinability formulas is the Taylor tool life equation:

$$Vt^n = C \tag{1}$$

where V = the cutting speed in fpm

T = tool life in minutes

C = constant dependent upon work material, tool material, geometry and cutting fluid

n = factor based on tool material

Accepted values of n are .125 for high speed steel, .25 for carbides and .68 for sintered oxide tools. (29)

The General Electric Carboloy (TM) CM program uses a form of the following empirical model developed by W. Gilbert:

$$V = \frac{A \times B \times C \times D \times E \times F \times G \times P \times Q^{.25}}{H^{1.72} \times T^{n} \times R^{.16} \times f^{.58} \times d^{.2}} \qquad (2)$$

Where V = cutting speed in fpm

A = scale adjusting factor for tool material

typical values are 180,000 for HSS

300,000 for carbides

1,500,000 for sintered oxides

B = factor for coolant used

typical values are 1.0 for dry

1.15 for cutting oils

1.25 for soluble oils

C = factor for work material,

typical values are 0.8 for carbon steel

1.05 for free cutting steel

1.1 for alloy steel

0.75 for cast iron

2.0 for free cutting brass

0.85 for aluminum alloys

0.90 for magnesium alloys

D = factor for work microstructure

typical values are 0.7 for austenitic steels

1.0 for most steel stock

1.4 for coarse spheroidized

E = factor for rough workpiece surface

typical values are 0.7 for sand cast

0.75 for sand cast and shot blast

0.8 to 0.95 heat treat scale

1.0 for clean surface

F = factor for type of tool

typical values are 1.0 for single point turning, boring, and facing tools, and most mills

0.7 for drills and form cutters

0.8 for reamers

G = factor for tool profile

typical values are 1.0 for sharp pointed tools with no entering angle to 1.5 for large nose radius and entering angle.

1.14 for drills

0.8 to 1.3 for face mills

1.0 for slab mills

0.8 for slot mills

P = tool material factor

typical values are 1.0 for HSS

5.0 for carbides

8.0 for ceramics

Q = amount of flank wear allowed, inches

H = Brinell hardness of the workpiece

R = number of cutting teeth on the tool

T = tool life in minutes

n = Taylor tool life exponent

f = feed in inches per revolution

d = depth of cut in inches

The actual formula used by the Carboloy (TM) program is based upon a workpiece of B1112 steel at 160 BHN and requires a material machinability factor and a hardness correction factor. Also, their formula is tailored to carbide tools and is not as general as the version given above. (30) This formula approximates actual cutting conditions fairly well and has been used to construct nomographs for given materials, charts for trading off parameters and as the basis for an analog computer. (31)

Another approach to predicting machinability data considers the machining process as a multiple state space problem of the form common in feedback control problems. A state space exists consisting of mathematical state elements for workpiece surface roughness, tool-workpiece kinematics, metal removal process stability, tool life, economic constraints and productivity. Each possible state is represented by a change of the state elements which may further influence other state elements. Using a parameter variance procedure that relates change in the state elements to the machining state space and evaluating the resulting state space, a prediction can be made of the expected machinability under set of machining parameters. The problem then becomes one of state space optimization around the desired machining characteristics. A heuristic search is made to identify the more promising machine states after varying individual parameters. The more promising machine states are then developed until an acceptable solution has been found. (32)

The disadvantage with using such formulas is that considerably more information is required as a starting point to obtain the desired information than is required from a tabular data base. However, data storage device requirements are much less. The data from the formulas is less exact than data from tabular data bases but can provide accuracy sufficient for planning purposes over a wide range of conditions.

RELATIONAL MACHINABILITY DATA BASES

Relational data bases employ another type of data structuring that is more powerful for the retrieval of data than either the hierarchial or computational methods above. The data elements are described and filed by the relationship

they have to other data. Each data relationship is distinct. The data can be viewed in any order and in any format. To access data, the user states his query in a language not dissimilar to Boolean algebra. For example, to determine what tool materials are used to cut AISI 4340 steel, the user's query might be "PROJECT(WMATL:4340 and TMATL: all)". The data base processor returns a list of tool materials that are used to cut AISI 4340 steel regardless of operation. New data is added by merging with the data of an existing relationship or by describing a new relationship.

The immediate advantages of the relational structure are two fold: First, access of data is quicker for more varied applications of the machinability data base. Second, updating and adding to data base is easier than is currently possible with tree structured data bases. One disadvantage is a relational data base requires considerably more computational processing support than either the hierarchial structure or the computational methods. If a query language is used as with CODASYL standard data bases (e.g., IDMS, DMS 1100, DBMS-10, etc.,) user training is extensive to realize the full capability of the data base system. (33, 34)

An interesting relational data base system for machinability is under development by Metcut Research Associates, Inc. under US Air Force contract. This system uses the ICAM Data Base Management System to store and retrieve data. In addition, the system provides statistical and mathematical modeling so that new data can easily be integrated into the data base. The mathematical modeling allows a knowledgable user to describe a machining process, to predict the performance of a machining operation for which detailed data may not exist, and to develop controls for a machining process. The statistical support

includes ANOVA variance testing, curve fitting and graphical as well as tabular output.

As with any true relational data base system, the user provides only the information that he has available as input. CODASYL structuring is used for data storage but is enhanced by menu driven commands that allows a user to traverse more than seventy trees to arrive at a desired data element effortlessly. (This is contrasted with the single tree system that is used with hierarchial data bases.) If the user has detailed, comprehensive information concerning the data that he is looking for, the tree structure quickly and efficiently isolates the desired data. On the other hand, if the user provides only generalized input, a broader data search is made. The system is interactive and appears relatively easy to use.

This system has not yet been released by the Air Force but interim reporting indicates that it is the first successful general purpose relational machinability data base. This system represents a major step forward in the design and utility of machinability data as it permits the growth of distributed machinability data processing in a computer integrated manufacturing system. A disadvantage, as with other relational data bases, is it requires a mainframe computer. (35)

FUTURE DEVELOPMENTS

An area for investigation with machinability data is distributed data base design. Current machinability data bases are by their very nature centralized. By centralized, all of the data resides on one computer in one data file. However, the information in a machinability data base has its origin in several other data bases. For example, a manufacturing resources planning system has

information on the time it takes to make certain parts on specific machines. Job control information and the scheduling and loading data could be used to flag inaccurate or questionable machinability specifications. Diagnostic machine control systems have considerable information concerning actual machine performance. Tool inventory lists provide tool materials and tool geometries in inventory. If this information could be accessed by the machinability data processor, the output from the processor has the potential to be more accurate and optimized for current operations. This technique of using the information existing on other machines or in other data bases is known as distributed data processing. (36) In a computer integrated factory, the capability of designing and implementing a distributed machinability data base exists with a high potential for rewards.

CONCLUSIONS

Machinability data bases in use today are either hierarchially structured or use empirical equations to generate machinablity data. The hierarchial systems provide similar functions to that provided by handbooks. The computational methods require more specific information to generate a desired data element. Both methods indicate starting points for process planning and design. Actual parameters when available should be used to modify the starting points.

Future effort is needed to integrate machinability data bases into the automated factory structure. The current work in relational data base design for machinability is a step towards this goal.

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